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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Solitons are pulsed waves exhibiting unique nonlinear properties. In electronics domain, electrical solitons had been passively produced by using nonlinear transmission lines. Prior to this proposal, our group built, for the first time, an active electrical circuit in a discrete platform, which robustly self-generated a stable, periodic train of electrical solitons. This was achieved by combining a nonlinear transmission line with a specially designed amplifier in a circular topology. The goal of this proposal was to build upon the demonstrated concept and to

15. SUBJECT TERMS
integrated circuits, solitons, electrical solitons, nonlinear transmission lines, oscillators, integrated oscillators, pulsed oscillators, THz electronics

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					617-496-9451

Report Title

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/01/16 2 3	O.O. Yildirim, D.S. Ricketts, D. Ham. Reflection Soliton Oscillator, IEEE Transactions on Microwave Theory and Techniques, (10 2009): 0. doi: 10.1109/TMTT.2009.2029025
2012/01/16 2 4	Xiaofeng Li, O. Ozgur Yildirim, Wenjiang Zhu, Donhee Ham. Phase Noise of Distributed Oscillators, IEEE Transactions on Microwave Theory and Techniques, (08 2010): 0. doi: 10.1109/TMTT.2010.2053062
2012/01/16 2 5	Donhee Ham, Xiaofeng Li, Scott Denenberg, Thomas Lee, David Ricketts. Ordered and chaotic electrical solitons: communication perspectives, IEEE Communications Magazine, (12 2006): 0. doi: 10.1109/MCOM.2006.273109
2012/01/16 2 6	D.S. Ricketts, Xiaofeng Li, D. Ham. Electrical soliton oscillator, IEEE Transactions on Microwave Theory and Techniques, (01 2006): 0. doi: 10.1109/TMTT.2005.861652
2012/01/16 2 2	D.S. Ricketts, Xiaofeng Li, Nan Sun, Kyoungho Woo, D. Ham. On the Self-Generation of Electrical Soliton Pulses, IEEE Journal of Solid State Circuits, (08 2007): 0. doi: 10.1109/JSSC.2007.900291

TOTAL: 5

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

X. Li, W. Andress, and D. Ham, "THz soliton and plasmonic science and technology," (invited) GOMACTECH, March 2008.

O. O. Yildirim and D. Ham, "Picosecond electrical soliton oscillator and THz electronics," (Invited) Int. Semicond. Device Research Symposium, College Park, MD, December 2007.

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
2012/01/16 2:	7	O. Ozgur Yildirim, Dongwan Ha, Donhee Ham. Fully Monolithic 18.7GHz 16Ps GaAs Mode-Locked Oscillators, IEEE RFIC Symposium. 2011/05/06 00:00:00, . : ,

TOTAL: 1

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received		Paper
2012/01/17 1!	9	David Ricketts, Donhee Ham. Electrical Solitons: Theory, Design, and Applications, Boca Raton, FL: CRC Press, (12 2010)
2012/01/16 2:	8	Xiaofeng Li, David Ricketts, Donhee Ham. Solitons in electrical networks (in McGraw-Hill 2088 Yearbook of Science and Technology), New York Chicago San Francisco Lisbon London Madrid Mexico City Milan New Delhi San Juan Seoul Singapore Sydney Toronto: McGraw-Hill, (01 2009)

TOTAL: 2

Patents Submitted

Patents Awarded

Awards

2012-2013 IEEE Distinguished Lecturer, Solid-State Circuits Society.
2012 Invited featured speaker at Harvard Thinks Big (8 Harvard faculty members selected through campus-wide Harvard undergraduates survey)
2012 Harvard Yearbook Favorite Professor, Class of 2012.
2011 Harvard Yearbook Favorite Professor, Class of 2011.
2010 Honorary Master of Arts, Harvard.
2009 Gordon McKay Professorship, Harvard.
2008 MIT Technology Review Top 35 Young Innovator (TR35).
2007 John L. Loeb Associate Professorship, Harvard.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Dongwan Ha	0.45	
O. Ozgur Yildirim	0.79	
Kyoungho Woo	0.05	
FTE Equivalent:	**1.29**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Donhee Ham	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Scott Denenberg	0.00	Electrical Engineering
Ahmad Khairi	0.00	Electrical Engineering
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 2.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
O. Ozgur Yildirim
Kyoungho Woo

Total Number: **2**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Scientific Progress:

Statement of the problem studied

Solitons are short-duration pulsed waves, which can propagate in nonlinear dispersive media with unique nonlinear properties (and without changing their shape in lossless case). Their unique nonlinear properties have long captivated scientists. Electrical solitons, which had been passively produced using nonlinear transmission lines, are especially interesting, for they allow the use of the soliton physics in easily accessible electronics media. Prior to this proposal, by combining a specially designed amplifier with a nonlinear transmission line in a circular topology, we built for the first time an active electrical circuit in a discrete platform, which robustly self-generated a periodic train of electrical solitons [1-6]. This robust electrical analogue of mode-locked soliton lasers had not been built before, as oscillating tend towards instability. In our oscillator, the amplifiers tamed the unruly solitons [1, 2]. The goal of this proposal was to build on this demonstrated concept, and develop electrical soliton oscillators in integrated forms with improved speed, e.g., with the pulse duration into the picosecond regime. Better understanding the phase noise process of the electrical soliton oscillator constituted another integral part of the problems to be studied.

Summary of the most important results [7-16]

(1) Chip-scale CMOS integrated soliton oscillator of the circular topology: In this work, we partially integrated the circular soliton oscillator in CMOS technology [7]. Specifically, the special amplifier with the level-dependent gain with saturable absorption was implemented with 0.18um CMOS technology, and the varactors (pn junction diodes) of the nonlinear transmission line were implemented with the same CMOS technology. The inductors of the nonlinear transmission line were created by bonding gold wires back and forth between the pads on the CMOS chip and metallic pads on a glass substrate, where the CMOS chip was placed. Bonding was done by using an automated bonding machine to ensure consistency in wire length, with the estimated inductance variation from inductor to inductor with less than 5%. The use of the bonding wires for inductors is to ensure high-enough quality of the nonlinear transmission line. The oscillator oscillated from 0.9 to 1.9 GHz, with the pulse width ranging from 293 to 400 ps. This work represents the first chip-scale mode-locked system in any field.

(2) Proof-of-concept discrete soliton oscillators with a new, reflective topology: We built reflection soliton oscillators, a new soliton oscillator topology, which self-start and self-generate a periodic train of short-duration soliton pulses [8]. The oscillator consists of a nonlinear transmission line, whose one end is connected to a special amplifier and the other end is open. In steady state, a self-generated sharp soliton pulse travels back and forth on the nonlinear line, reflected at both ends of the line due to the impedance mismatches. The amplifier produces a negative resistance for large signals and a positive resistance for small signals, and thus, the reflection from the amplifier provides gain for the main portion of the pulse to compensate loss, and attenuates small perturbations, which abound in the line due to its nonlinear properties, to ensure oscillation stability. The nonlinear line substantially sharpens the pulse. This work is in contrast to our earlier circular soliton oscillator, where the pulse is circulated instead of being reflected. Due to the reflection based operation, the reflection soliton oscillator is at least two times smaller than the circular soliton oscillator, and the energy efficiency is higher in the reflection soliton oscillator. An additional pulse sharpening mechanism provided at the open end of the nonlinear line further compresses the pulse. In an experimental prototype (discrete prototype for proof of concept), a duty cycle as short as 4.6% was attained with a pulse repetition period of 9.7 ns and a pulse width of 445 ps. In another prototype, we put the reflection soliton oscillator in a phase-locked loop for frequency locking, where the phase-locked loop circuit was partially integrated with CMOS 0.18 um technology.

(3) Integrated 16-ps GaAs mode-locked oscillators of the reflection topology: In this work, we developed a mode-locked electrical oscillator (self-sustained pulse generator) fully integrated in GaAs [9]. It uses our reflection-based mode-locking, described in the previous immediate section, and attains a 16-ps pulse width at 18.7-GHz pulse repetition rate. This is the fastest electrical mode-locked oscillator to date, and the first integration of the reflective mode-locked electrical oscillator. It works by sending a pulse back and forth on a coplanar waveguide with reflections at both ends. The reflection occurs with level-dependent gain at one end of the coplanar waveguide, and this process enables pulse formation as well as its stabilization. The measurement was done in time domain using an Agilent 93-GHz 86100C sampling oscilloscope. To ensure a definite phase relationship between a trigger and the oscillator signal, we used injection locking.

(4) Phase-noise theory of distributed oscillators including soliton/pulsed oscillators: We for the first time conducted a general analysis of phase noise in distributed oscillators including soliton oscillators, whose essence was experimentally verified [10]. It has thus far been unclear how to calculate the phase noise of soliton oscillators, and it has been unknown whether or not its phase noise would be better than sinusoidal oscillators. The difficulty in the phase noise calculation of distributed oscillators, especially in pulse oscillators such as soliton oscillators, is due to a large number of voltage and current variables in transmission lines and a large number of distributed noise sources. Building up from Kaetner's phase noise work, our method provides physical insight into the problem in an N-dimensional state space where N is the total number of voltage and current variables, and facilitates direct application to distributed oscillators. We showed that linear pulse oscillators have better phase noise than sinusoidal oscillators, against the usual thermodynamics argument, due to the shorter time a sharper pulse is

exposed to a given noise perturbation. In the soliton pulse oscillator, however, due to amplitude-dependent speed of solitons, amplitude-to-phase conversion can significantly contribute to phase noise. This study highlights useful design strategies. The linear pulse oscillator can achieve very good phase noise, if its active circuit is designed to produce a very narrow pulse. Second, if the amplitude-to-phase noise conversion in the soliton oscillator can be mitigated by a proper active circuit design to reduce amplitude error's lifetime, due to soliton's sharpness, the soliton oscillator can yield very good phase noise.

(5) Proof-of-concept discrete soliton-based chaos oscillators: Chaos can be generated in various nonlinear media, such as hydrodynamic systems, optical fibers, and electronic circuits. Chaos generated from electronic circuits is especially interesting, as it greatly facilitates the examination of chaotic behaviors, and also it can be used for truly random number generation. There exist various electronic chaos generators such as Chua’s circuits, and these circuits generate low-dimensional chaos. High-dimensional chaos in electronics can be attained by coupling these low-dimensional chaotic behaviors, but stand-alone electronic high-dimensional chaos generators have seldom been reported. In this work, we developed such an electrical oscillator that intrinsically generates high-dimensional chaos [11, 12]. This oscillator combines an amplifier and a nonlinear transmission line in a circular topology as in some of our electrical soliton oscillators, but this time, we design the amplifier in such a way that it can promote the unruly behaviors of solitons and their collisions maximally. The oscillator was experimentally examined, and the Lyapunov analysis as well as the spectral measurement confirmed the generation of chaos. Furthermore, the analysis of the acquired data indicates correlation dimensions of about 11.

Bibliography

1. D. Ricketts, X. Li, and D. Ham, “Electrical soliton oscillator,” IEEE Transactions on Microwave Theory and Techniques (T-MTT), vol. 54, no. 1, pp. 373-382, Jan. 2006.
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4. D. Ricketts, X. Li, and D. Ham, “Electrical soliton modelocking (invited cover article),” IEEE Laser & Electro-Optics Soc. (LEOS) Newsletter, vol. 20, no. 3, pp. 4–11, June 2006.
5. W. Andress, D. Ricketts, X. Li, and D. Ham, “Passive and active control of regenerative standing and soliton waves (invited paper),” Proceedings of IEEE Custom Integrated Circuits Conference (CICC), pp. 29-36, Sep. 2006.
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8. O. O. Yildirim, D. Ricketts, and D. Ham, “Reflection soliton oscillator,” IEEE Transactions on Microwave Theory and Technique (T-MTT), vol. 57, no. 10, pp. 2344-2353, Oct. 2009.
9. O. O. Yildirim, D. Ha, and D. Ham, “Fully monolithic 18.7-GHz 16-ps GaAs mode-locked oscillators,” Proceedings of IEEE Radio-Frequency Integrated Circuits (RFIC) Symposium, pp. 243-246, June 2011.
10. X. Li, O. O. Yildirim, W. Zhu, and D. Ham, “Phase noise of distributed oscillators,” IEEE Transactions on Microwave Theory and Techniques (T-MTT), vol. 58, no. 8, pp. 2105-2117, August 2010.
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12. O. O. Yildirim and D. Ham, “Self generation of chaos from electrical solitons,” APS March Meeting, Dallas, TX, Mar. 2011.
13. D. Ham, X. Li, S. Denenberg, T. H. Lee, and D. S. Ricketts, “Ordered and chaotic electrical solitons: communication perspectives,” IEEE Communication Magazine, vol. 44, no. 12, pp. 126-135, Dec. 2006.
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16. D. Ricketts, X. Li, and D. Ham, “Soliton & nonlinear wave electronics,” in Circuits at the Nanoscale (Ed: K. Iniewski), CRC Press, 2008.
17. X. Li, W. Andress, and D. Ham, “THz soliton and plasmonic science and technology,” (Invited) GOMACTECH, March 2008.
18. O. O. Yildirim & D. Ham, “Picosecond electrical soliton oscillators & THz electronics,” (Invited) Int. Semicond. Device Research Symp., College Park, MD, Dec. 2007.

Technology Transfer

Final Progress Report (FPR)

Principal Investigator: Donhee Ham
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(E-mail) donhee@seas.harvard.edu (Tel) 617-496-9451
(Research web) http://www.seas.harvard.edu/~donhee

Project Title: On-chip electrical soliton modelocked oscillators for ps pulse self-generation & THz electronics

Agreement Number: W911NF-06-1-0290

Proposal Number: 49582-EL

Reporting Period: 08/01/2006 – 01/31/2010

Program Manager: Dr. Dwight Woolard

<u>Abstract (200 words)</u>:

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Bibliography

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2. D. Ricketts, X. Li, M. DePetro, and **D. Ham**, "A self-sustained electrical soliton oscillator," *IEEE MTT-S International Microwave Symposium* (*IMS*), June 2005.
3. D. Ricketts and **D. Ham**, "A chip-scale electrical soliton modelocked oscillator," *IEEE Int. Solid-State Circ. Conf.* (*ISSCC*) *Dig. Tech. Papers*, pp. 432-433, Feb. 2006.
4. D. Ricketts, X. Li, and **D. Ham**, "Electrical soliton modelocking (*invited cover article*)," *IEEE Laser & Electro-Optics Soc.* (*LEOS*) *Newsletter*, vol. 20, no. 3, pp. 4–11, June 2006.

5. W. Andress, D. Ricketts, X. Li, and **D. Ham**, “Passive and active control of regenerative standing and soliton waves (*invited paper*),” *Proceedings of IEEE Custom Integrated Circuits Conference* (*CICC*), pp. 29-36, Sep. 2006.
6. D. Ricketts, X. Li, and **D. Ham**, “Taming the electrical soliton – A new direction in picosecond electronics (*invited paper*),” *Proceedings of IEEE Radio Frequency Integrated Circuits* (*RFIC*) *Symposium*, pp. 33–36, June 2006.
7. D. Ricketts, X. Li, K. Woo, N. Sun, & **D. Ham**, “On the self-generation of electrical soliton pulses,” *IEEE J. Solid-State Circ.*, vol. 42, no. 8, pp. 1657–1668, Aug. 2007.
8. O. O. Yildirim, D. Ricketts, and **D. Ham**, “Reflection soliton oscillator,” *IEEE Transactions on Microwave Theory and Technique* (*T-MTT*), vol. 57, no. 10, pp. 2344-2353, Oct. 2009.
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